SUPERCONDUCTING 72 MHZ BETA=0.077 QUARTER-WAVE CAVITY FOR ATLAS

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Abstract

A 72 MHz superconducting (SC) niobium quarter-wave cavity (QWR) optimized for $\beta=0.077$ has been built and tested as part of a beam intensity upgrade of the ATLAS SC heavy-ion linac. The two-gap cavity, designed to accelerate ions over the velocity range $0.06<\beta<0.12$ and provide 2.5 MV of accelerating voltage per cavity at T=4.5 Kelvin, is based on a highly optimized electromagnetic design to reduce surface electric and magnetic fields. Horizontal electropolishing on the complete cavity with the helium jacket is similar to that performed on 1.3 GHz ILC-type cavities and is a first for a low-β TEM cavity. This development is part of a broader effort to demonstrate ~120 mT surface fields with $R_s \sim 5$ nΩ in 2 K operation for low-β cavities with the aim of substantially reducing footprints for future ion linacs. First rf cold test results show the highest accelerating gradients (13.4 MV/m, $l_{eff}=\beta\lambda$) and voltage/cavity (4.3 MV) achieved for this class of SC cavity.

INTRODUCTION

Primary development for phase I of the ATLAS Efficiency and Intensity Upgrade [1] includes a new high-efficiency 60.625 MHz CW radio frequency quadrupole injector [2] and a one new cryomodule of 7 SC cavities required to provide 17.5 MV of accelerating potential over 5 meters. The new cryomodule will replace three existing 97 MHz split-ring cryomodules, dramatically increasing beam transport efficiency for both stable and radioactive ion beams by increasing overall acceptance and reducing emittance growth in the SC linac.

The required cavity voltage, V_{acc}=2.5 MV/cavity, at $\beta=0.077$, is roughly two times higher than for the present state-of-the-art for this low beta [3]. To achieve this, a combination of improved rf design [4] and improved cavity processing techniques have been developed.

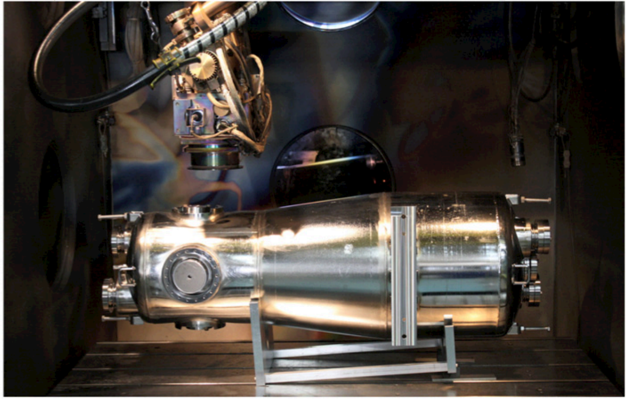

Figure 1: Final cavity welding in e-beam weld chamber.

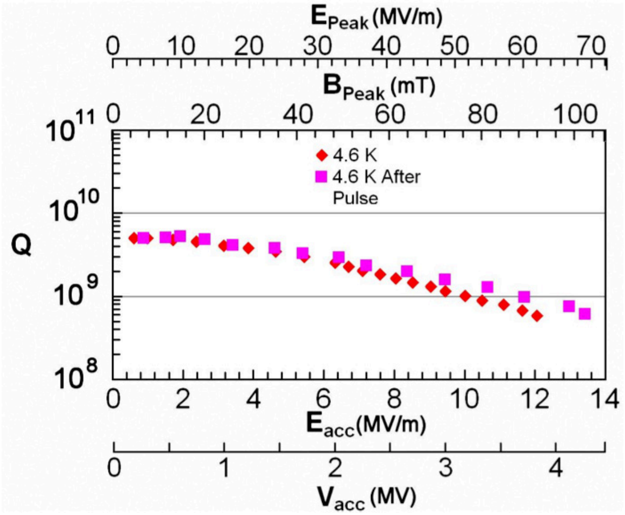

Figure 2: First cold test results for a prototype 72 MHz $\beta=0.077$ quarter-wave resonator ($l_{eff}=\beta\lambda$).

INITIAL RESULTS

First cold test results have been measured on the prototype 72 MHz cavity following completion of fabrication (see Figure 1.) and subsequent heavy, 150 μm, electropolishing. Further work is ongoing (*e.g.* baking, re-rinsing), however, results shown in Figure 2. already constitute an advance in performance for quarter-wave cavities for this velocity range.

The low-field quality factor of $5\text{x}10^9$ corresponds to a residual surface resistance of 3.1 nΩ. The maximum cavity accelerating gradient of E_{acc}=13.4 MV/m ($l_{eff}=\beta\lambda$) was measured following 1-1/2 hours of short pulse conditioning with 4.5 kW peak power. The accelerating potential at this gradient, 4.3 MV, is easily the largest for any SC cavity in this velocity range. The ATLAS upgrade requirement is 2.5 MV/cavity where P_{in}=5 Watts for this test. At least 10 Watts/cavity are available in the full module. The cavity also provides practical CW acceleration up to at least V_{acc}=3.5 MV (P_{in}=18 Watts) for T=4.5 K. Based on recent cavity results for Spiral 2 [5], a controlled 'in-situ' bake at 115°C for 48 hours will be performed prior to the next cooldown in order to reduce Q-slope for medium-to-high gradients.

The cavity is also under study for T=2 K with the goal of achieving $B_{peak}\sim 120$ mT, $R_s\sim 5$ nΩ and a useful CW accelerating potential of $V_{acc}\sim 5$ MV. Successful development would provide an attractive option for megawatt-class CW linacs in areas of applied science and technology such as for medical isotope production, national defense, and accelerator driven systems.

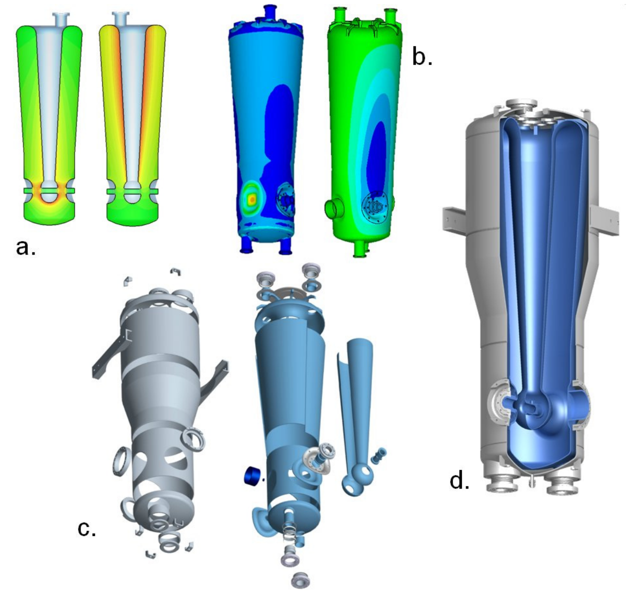

Figure 3: Electromagnetic (a.) and mechanical (b.) simulations. Cavity subcomponents (c.) and the complete cavity model (d.)

DESIGN AND FABRICATION

Electromagnetic Design

Detailed electromagnetic (EM) design and optimization of the 72.75 MHz QWR has been discussed previously [4]. The guiding principle has been to provide the maximum accelerating gradient along the linac with large acceptance and minimal beam steering. The frequency is the 6th multiple of the ATLAS 12.125 MHz master oscillator and is the lowest practical value for fabrication and processing. The most innovative EM design feature is the conical-shaped outer housing which reduces B_{peak}/E_{acc} by at least 20% compared to a straight cylinder but requires no additional space along the beam axis as some space is already required to join adjacent cavities at the beam ports. Other important EM parameters are listed in Table 1.

Mechanical Design

The most important mechanical consideration for this thin-walled (3 mm) structure formed from high purity (RRR>250) fine-grained niobium sheet is mechanical stability in the presence of various sources of microphonics. These include helium bubbling for T>2.2 K and mechanical vibrations coupled into the cavity from the accelerator environment. Other important mechanical considerations include the need to tolerate differential pressures of 15 PSIA at room temperature and >25 PSIA at cryogenic temperatures without permanent detuning and to tolerate the application of a slow tuner force at the beam ports of up to 4500 lbs per side.

The following specific mechanical design features have been included based on detailed ANSYS simulations performed in collaboration with Advanced Energy Systems.

Table 1: Primary Electromagnetic and Mechanical Properties for the 72 MHz QWR ($l_{eff}=\beta\lambda$).

Parameter	**Value**	**Units**
Frequency	72.750	**MHz**
Peak Beta	0.077	
QRs	26.4	**Ohm**
R/Q	576	**Ohm**
$\beta\lambda$	31.75	**cm**
Design Voltage	2.5	**MV**
$\Delta f / \Delta E^2_{acc}$	-1.9	**Hz/(MV/m)^2**
$\Delta f / \Delta P$	-2.6	**Hz/Torr**
Tuning Sensitivity	~8	**kHz/mm**
At Eacc= 1 MV/m		
Stored Energy	0.375	**Joule**
E_{peak}	5.16	**MV/m**
B_{peak}	76.2	**mT**

- A set of eight large re-enforcing ribs on the torus at the top of the cavity (Figure 3.b., c. and d.) to reduce Δf/Δp and stiffen the center conductor
- A re-enforcing 'doubler' plate of 3 mm niobium welded onto each beam port for strength during slow tuning
- A 10 cm diameter flat region on the cavity wall 90° from the beam port to provide a compliant area for a fast piezo-electric tuner
- A niobium re-enforcing ring 180° from the fast tuner to compensate for a small increase in Δf/Δp due to the flat region

The final design has very low measured helium pressure sensitivity (see Table 1.) and more than a factor of 2 margin with respect to the niobium yield strength for all planned modes of operation. Additional design details are provided elsewhere [6].

Niobium Fabrication and Tuning

Niobium cavity sub-components are shown graphically on the right side of Figure 3c. The torus at the top, the dome at the bottom, the two halves of the center conductor and the beam port noses and re-enforcing plate are all formed with aluminium dies and niobium sheet. Sections of the outer housing were rolled from sheet. Smaller components including beam and coupling ports and re-enforcing ribs were machined or cut from cylindrical bar or niobium plate. All niobium electron beam welding on the prototype cavity was performed at Sciaky at a vacuum chamber pressure of 2×10^{-5} Torr or better.

Final tuning required some development due to the required fixed length of the conical-shaped outer housing once the angle was chosen. Here, course tuning was performed using wire EDM to cut 2.2 cm lengths of niobium from the top of the center conductor and the lower cylindrical cavity section. Measured sensitivity was 55 Hz/μm. For the prototype this was done in three steps.

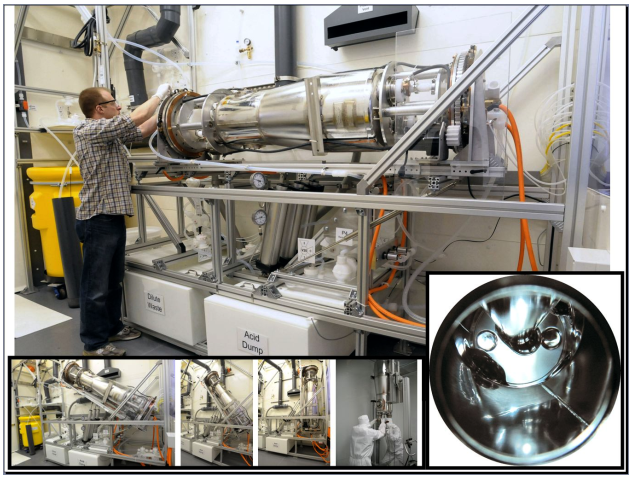

Figure 4: Horizontal electropolishing on a QWR.

For the six production cavities this will be reduced to 1-2 cutting steps. After final electropolishing and evacuation (+20 kHz frequency shift) and cool down from room temperature (+90 kHz), the final cavity frequency at T=4.6 K was measured to be 72.755 MHz, within a few kHz of the nominal frequency

CAVITY PROCESSING

Electropolishing

A new electropolishing system at ANL for co-axial quarter- and half-wave SC cavities is similar to that used for 1.3 GHz ILC-type cavities. Operation is straightforward based on several years experience with the existing ANL system for elliptical cavities. However, the system also includes direct water cooling applied to the outside of the niobium using the liquid helium jacket. The technique provides substantial additional control of the procedure since the rate of acid flow through the cavity is de-coupled from the requirement to maintain the cavity surface at a fixed temperature (25-30^{o}C).

Mechanically the system is similar to the ILC-cavity system, except that a single aluminium cathode is replaced by four separate cathodes, one through each of the four coupling ports, two at each end of the cavity. During EP the cavity rotates at ~1/2 rpm and the anode/cathode voltage is fixed at 18 V.

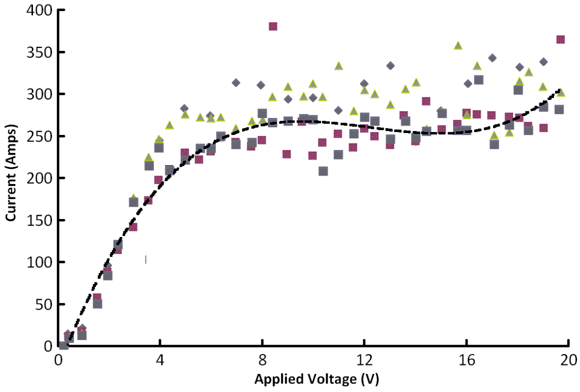

Figure 5: I-V curves measured during EP.

Measured I-V curves, shown in Figure 5., have the characteristic plateau in current versus applied voltage that is more distinct than for curves measured at ANL for elliptical cavities. This probably indicates more optimal electropolishing over most of the QWR surface.

A total surface removal of 150 μm of niobium for the QWR was performed in two separate steps over the course of two days and with a total electropolishing time of 12 hours. The time required to mount, polish, dismount and ultrasonic clean the cavity is two (man-)days, about the same as for buffered chemical polishing where the cavity must be dismounted and flipped midway through the etching for uniform removal. A photograph taken through one of the four coupling ports following EP is shown in the inset in Figure 4.

For final preparation, the cavity was rinsed in a new vertical high-pressure water rinse stand and assembled in a class 100 clean room adjacent to the existing ILC-cavity clean room area. The measured onset of field emission was between E_{peak}=35-40 MV/m. It is presently unknown whether the quench at E_{peak}~70 MV/m is due to field emission or a defect. The cavity is equipped with second sound thermometry to be used to investigate the source of the quench.

CONCLUSION

The fabrication of an advanced quarter-wave resonator design for β=0.077 at 72.75 MHz has been completed. Horizontal electropolishing on the completed cavity was performed for the first time. Initial cold test results at T=4.6 K show remarkably good performance, easily exceeding the ATLAS requirements. Maximum performance parameters are E_{acc}=13.4 MV/m ($l_{eff}=\beta\lambda$), E_{peak}=69 MV/m, B_{peak}= 102 mT and V_{acc}=4.3 MV. Further work including low temperature baking, re-rinsing and 2 Kelvin studies are under way.

ACKNOWLEDGEMENT

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